

Multi-Way and Poly-Phase Wideband Differential Phase Shifter Based on Metamaterial Technology

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Abstract: This paper presents multi-way and poly-phase differential phase shifter (DPS) based on metamaterial technology to realize delay lines of equal length. The proposed phase shifter provides the required phase shift relative to the reference line over a wide bandwidth. Several DPS phase shifter designs were fabricated and tested to verify their performance. Measured results show that the proposed phase shifter has phase deviation of less than $\pm 4^\circ$ and return-loss better than 10-dB with an insertion-loss of less than 1 dB across 2.2 to 4.4 GHz.

Keywords: Differential phase shifter (DPS), wideband, metamaterials, stepped impedance resonator (SIR).

1. Introduction

Differential phase shifter (DPS) structures are widely used in different microwave systems such as phased-array antennas and adaptive beamforming systems [1], [2] to provide constant phase difference between two parallel paths. Conventional differential phase shifters are composed of a reference line and a delay line. DPS usually require different reference lines to provide various differential phase shifts over a specified frequency range. This results in both complex multi-way and poly-phase structures that are bulky. Additionally, in a conventional DPS the reference and delay lines are of different lengths that precludes dense integration to realize a more compact wireless communication system. Ideally, DPS should provide useful shift values with small phase deviation, operate over a wide frequency range, are low-loss and compact devices.

Traditional Schiffman phase shifters use edge-coupled lines to provide a 90° phase shift however they suffer from undesirably high phase deviation typically of $\pm 10^\circ$ [3]. Also, tight-coupling is necessary to achieve a large fractional bandwidth of about 80%. In [4] it has been shown acceptable phase ripple can be achieved using a 90° phase shifter with T-shaped open-stub loaded transmission-line. This phase shifter achieves a fractional bandwidth of 82% with a $\pm 6.4^\circ$ phase ripple. In [5] it is shown that by substituting the open-stub with a pair of multi-section radial stubs a wider bandwidth can be realized. In [6], a wideband phase shifter is implemented on a multilayer substrate using an elliptical-shaped broadside coupled structure that exhibits a phase shift range of 30° - 90° . In [7] it is shown that by loading the phase shifter with reactive elements the phase shift can be increased to $90^\circ \pm 4^\circ$. The fractional bandwidth of this phase shifter is 80%. In [8], microstrip slot-line transition is used to realize a wideband phase shifter on a single layer of substrate. This phase shifter able to provide phase shifts in the range

of 45° - 90° with minimal loss in the C-band and is relatively small. However, its differential phase stability is compromised. In [9], a single layer wideband phase shifter is proposed that provides a phase range of 45° - 180° . The device uses an L-shaped network combined with one section of coupled lines to obtain a fractional bandwidth of 100% but it has a high phase deviation of $\pm 8^\circ$. In [10] a 90° phase shifter is designed to operate across 3 GHz to 10 GHz with phase error of $\pm 5^\circ$ by using two composite right/left handed (CRLH) transmission lines. In [11], a multi-way poly-phase DPS is reported. This phase shifter uses feed-forward coupled line sections as the common component. However, in this design by increasing phase shift values the length of the main line correspondingly increase [12], [13]. In [14], an equal length multi-way differential phase shifter based on metamaterials is presented. The phase shifter uses complementary split-ring resonators (CSRRs) to provide arbitrary phase shifts across a bandwidth of 65%. In the aforementioned phase shifter structures, the reference and main lines are of different lengths, and the length of main line is affected by the magnitude of the required phase shift.

This paper presents a new configuration of an equal length multi-way and poly-phase DPS based on metamaterial structures. The degree of phase shift is only determined by the parameters of the metamaterial structure Unlike conventional transmission-lines the physical properties of metamaterial structures are independent of frequency. This property is exploited here in the design of compact phase shifters. Phase shifters based on metamaterial technology are realized with three different phase shifts of 60° , 75° and 90° that operate over 2.2 to 4.4 GHz for WiMAX and Bluetooth applications. Compared to other phase shifters based on SRR in [15] that provide a limited phase shift of 34° across a narrowband of 5.85 GHz to 6.05 GHz, the proposed structure can provide larger phase shifts and is significantly smaller. The performance of the phase shifter was verified practically. The detailed equivalent circuit model and theoretical analysis of the proposed DPS are presented in section 2. In section 3, the design configuration of the proposed DPS is described. The theoretical results are verified with experimental results in section 4, and the paper is concluded in section 5.

2. Design Theory and Analysis

A standard uniform microstrip transmission-line which is loaded with a square SRR slot in the ground-plane is known to operate over a narrow bandwidth. Therefore, to improve its bandwidth performance of a standard uniform transmission-line structure it is modified as depicted in Fig. 1. It comprises of a unique stepped impedance split-ring resonator (SI-SRR), which widens the bandwidth through broadband matching. SI-SRR encloses a smaller ring resonator that is connected to it centrally, which creates a transmission zero. To improve the return-loss the input and output feedlines are connected to each other with a U-shaped transmission-line. The structure includes two circular split-ring resonators (CSRRs) near the input/output ports. SI-SRR and the two CSRRs determine the upper and lower cutoff frequencies as well as the phase of the proposed microstrip structure. The phase shift of the structure can be finely controlled by changing the radius of the two CSRRs.

The structure in the top and bottom layers represent metamaterial phase alignment network that are used to realize equal physical lengths of the reference and the delay lines. The two CSRRs can finely control the electrical length of a transmission-line, and consequently different phase shifts can be achieved by simply changing the radius of the metamaterial phase alignment network without altering any other parameters of the main and the reference lines. The advantage of this technique is marginal effect on the physical length of the transmission-line. The metamaterial CSRR configuration and its equivalent lumped element are shown in Fig. 2.

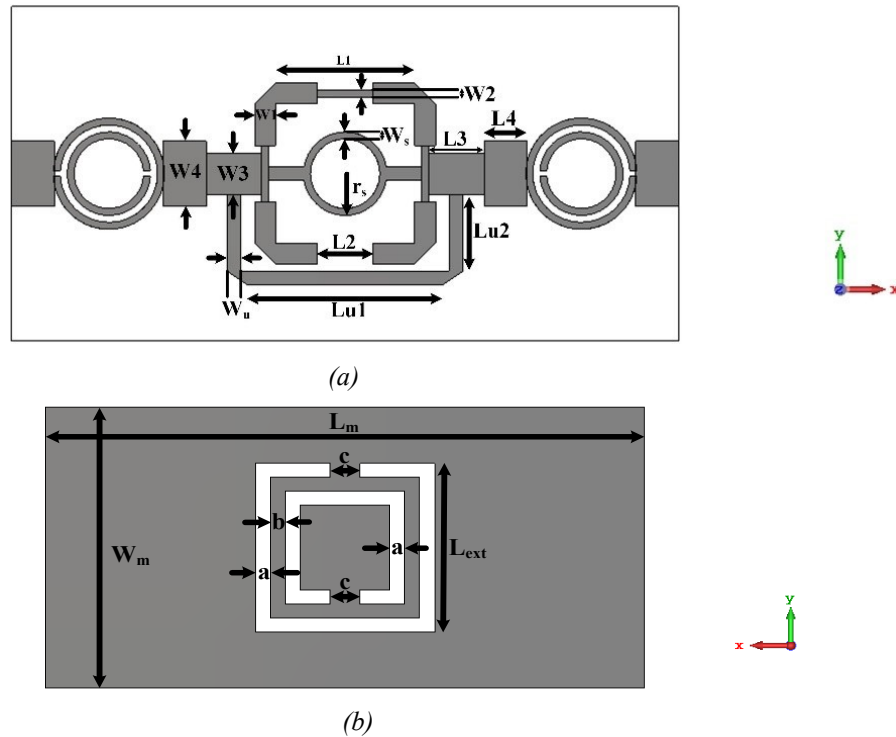


Fig. 1. Geometry of the proposed phase shifter based on metamaterial technology, (a) Top layer of main lines, and (b) Bottom layer includes a square CSRR.

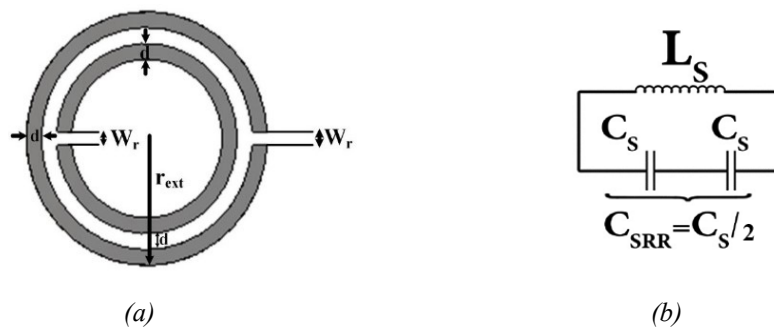


Fig. 2. (a) CSRR configuration, and (b) Equivalent lumped element model.

Reflection (S_{11}) and transmission (S_{21}) coefficients were used to retrieve the permeability of SRR in Fig. 2(a) based on the approach described in [16] using the following equation:

$$n = \frac{1}{jK_o d} \log \left[\frac{S_{21}}{1 - S_{11} \left(\frac{z-1}{z+1} \right)} \right] \quad (1)$$

Where K_o and d are the wave vector of the incident wave and the thickness of the substrate, respectively. z is impedance of the microstrip-line and n represents the refractive index. The permeability μ can then be computed from:

$$\mu = nz \quad (2)$$

The S-parameters response and extracted permeability of the SRR in Fig. 3 show the SRR has negative permeability around its resonance frequency.

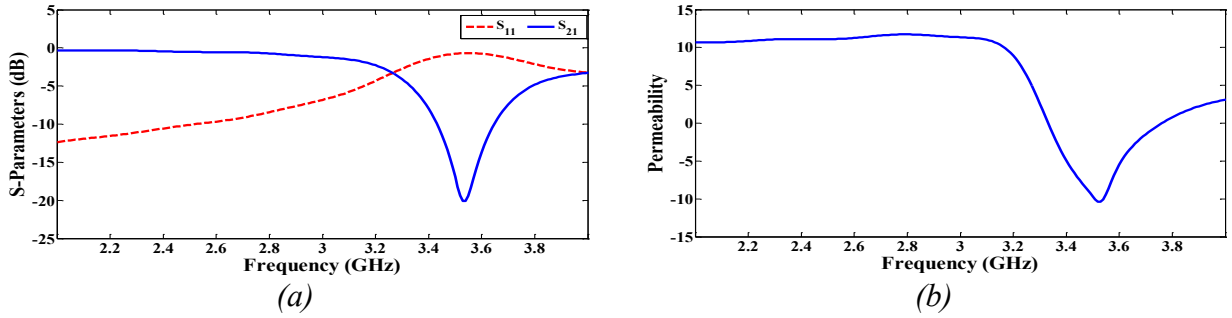


Fig. 3. (a) S-parameter response of the SRR, and (b) extracted permeability (μ).

The simplified equivalent circuit model of the proposed DPS in Fig. 1 is shown in Fig. 4. The structure in the middle is represented by the equivalent circuit in section P_1 , where the ground-plane square SRR slot is represented by inductance L_c and C_c . In part, P_1 the parameters L_{eq} and C_{eq} represent the inductive and capacitive effects resulting from the SI-SRR, central ring resonator, and U-shaped transmission-line. The equivalent circuit model of the ground-plane square SRR slot is electrically coupled to SI-SRR via capacitance C . SRRs at the input and output are represented by the equivalent circuit in sections P_2 .

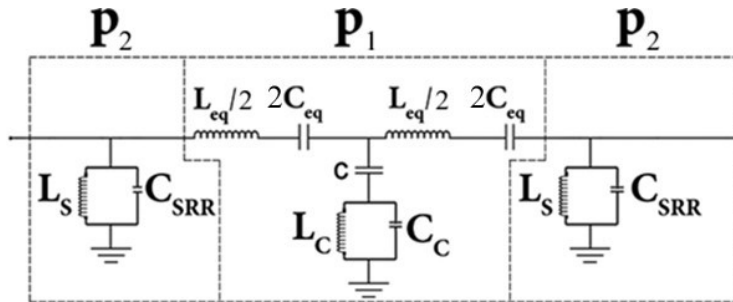


Fig. 4. Simplified equivalent circuit model of the proposed DPS constituted from the phase alignment network composed of P_1 and P_2 .

The electrical length of section P_1 and its characteristic impedance can be determined from the following equations [14]:

$$\cos(\theta_{P_1}) = 1 + \frac{Z_s(j\omega)}{Z_p(j\omega)} \quad (3)$$

$$Z_{P_1} = \sqrt{Z_s(j\omega)[Z_s(j\omega) + 2(Z_p(j\omega))]} \quad (4)$$

Where Z_s and Z_p represent the series and shunt impedances, respectively, in the equivalent T-circuit model. The characteristic impedance and electrical length are given by

$$\theta_{P_1} = \cos^{-1}(1) + \frac{c(\omega^2 L_{eq} C_{eq} - 1)(1 - \omega^2 L_c C_c)}{2C_{eq}[(\omega^2 L_c C_c - 1) + \omega^2 L_c C]} \quad (5)$$

$$Z_{P_1} = \sqrt{\frac{(\omega^2 L_{eq} C_{eq} - 1)}{C_{eq}} \left[\frac{1}{\omega^2 C} + \frac{L_c}{(\omega^2 L_c C_c - 1)} - \frac{(\omega^2 L_{eq} C_{eq} - 1)}{(\omega^2 L_c C_c - 1)} \right]} \quad (6)$$

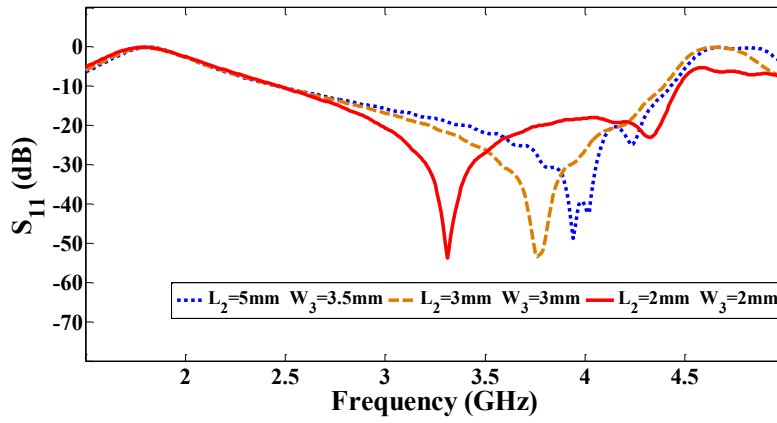
Component values for part P_1 and P_2 were extracted using the equations in [17-20] for three main lines to provide a phase shift of 60° , 75° and 90° , which are in Table 1.

Table 1: Extracted lumped components of main lines for phase shifts of 60° , 75° and 90° .

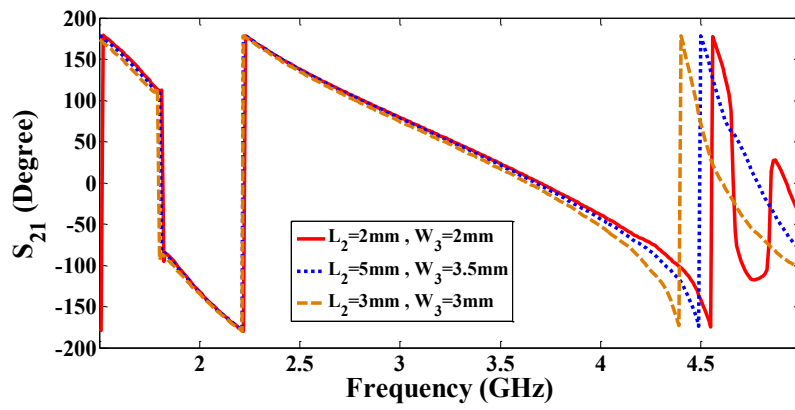
$\Delta\phi$	60°	75°	90°
L_{eq} (nH)	0.007	0.007	0.007
C_{eq} (pF)	0.0034	0.0034	0.0034
L_c (nH)	7.72	7.72	7.72
C_c (pF)	0.4	0.4	0.4
C (pF)	0.5	0.5	0.5
L_s (nH)	2.24	1.96	1.56
C_{SRR} (pF)	1.06	0.95	0.86

3. Parametric Study

Without perturbing the metamaterial phase alignment networks in Fig. 1 the bandwidth of the proposed differential phase shifter can be adjusted by altering the dimensions of L_2 and W_3 , while keeping all other parameters are fixed as shown in Fig. 5(a). There is no change in the return-loss from 1.5 GHz to 2.5 GHz for change in L_2 and W_3 . When L_2 and W_3 are 2 mm and 3 mm, respectively, the return-loss minima occur at around 3.35 GHz. However, the minima shifts to 4 GHz when L_2 and W_3 are 5 mm and 3.5 mm, respectively. According to Fig. 5(b), the dimensions of the L_2 and W_3 have virtually no effect on the phase response between 2.2 GHz to 4 GHz. However, in the proposed DPS structure the adjustment of the phase angle can be implemented by altering a single parameter, i.e. the radius of the phase alignment network. Fig. 6 reveals the slope of the phase shifts slightly towards lower frequency as r_{ext} is increased, and there is a moderate change in return-loss. Radius of ring (r_{ext}) has no impact on the bandwidth of structure.

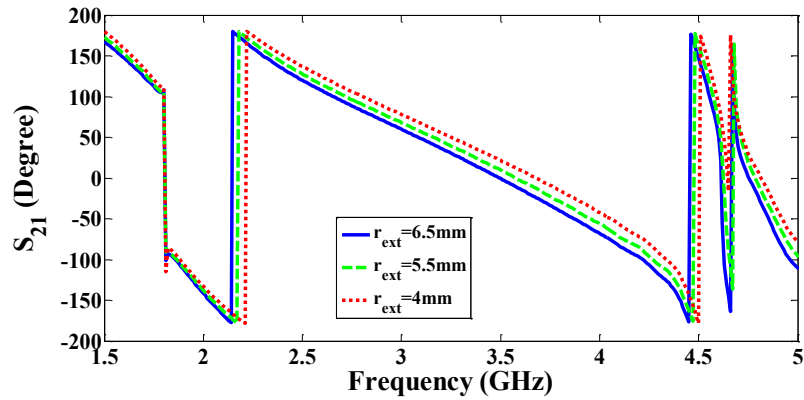


(a)

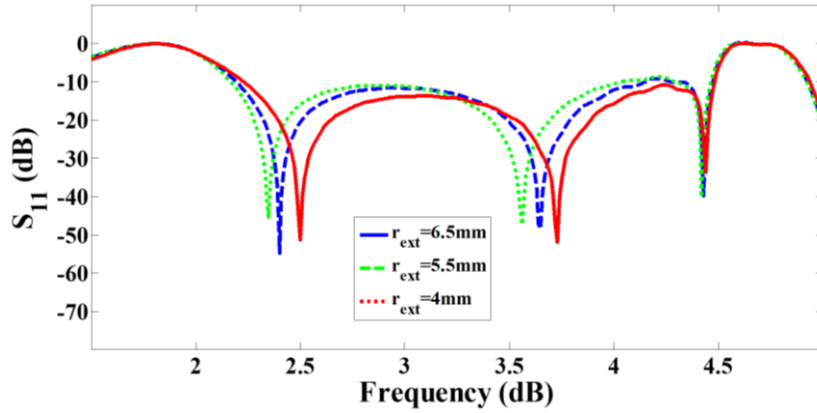


(b)

Fig. 5. Simulated return-loss and transmission angle frequency response of DPS as a function of L_2 and W_3 , (a) S_{11} (dB), and (b) $\angle S_{21}$ ($^\circ$)



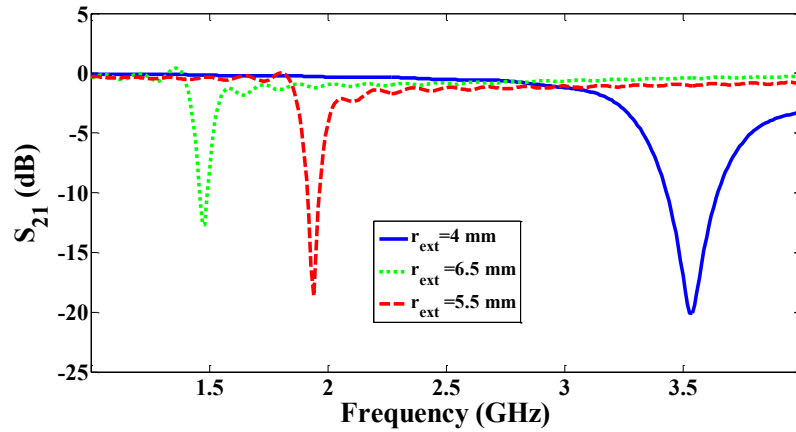
(a)



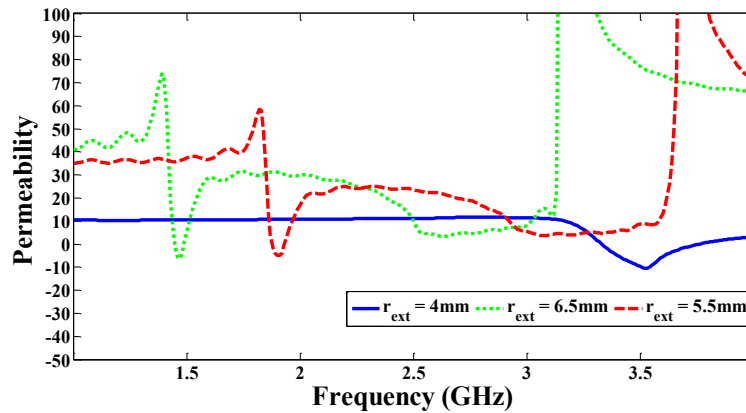
(b)

Fig. 6. Simulated transmission angle and return-loss frequency response of DPS as a function of r_{ext} , (a) $\angle S_{21}$ ($^\circ$), and (b) S_{11} (dB).

Fig. 7 shows how the resonant frequency and permeability of the SRR are affected by r_{ext} . It shows regions in the frequency band where the permeability is negative and how this shift with change in r_{ext} .



(a)



(b)

Fig. 7. Effect of r_{ext} on the SRR's (a) transmission response, and (b) permeability.

4. Experimental Results and Discussion

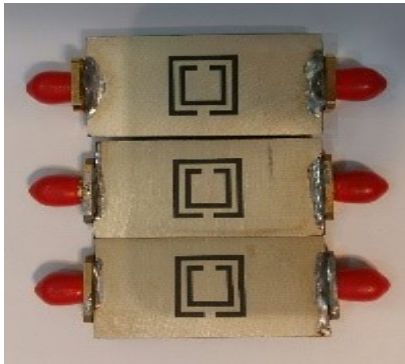
As mentioned earlier the proposed DPS was designed and fabricated on Rogers Duroid 5870 substrate with a relative permittivity (ϵ_r) of 2.33, loss-tangent of 0.0012 and a thickness (h) of 1.575 mm. CST Microwave Studio™ software was used to optimize the DPS's performance. Physical dimensions of the three phase shifters are given in Table 2. Dimensions of two metamaterial phase alignment networks to provide phase shifts of 60° , 75° and 90° are given in Table 3. Fig. 8 shows a photograph of the three delay lines and a reference line that were fabricated and measured.

Table 2: Dimensions of the DPS main lines for phase shifts of 60° , 75° and 90° . (Units in mm)

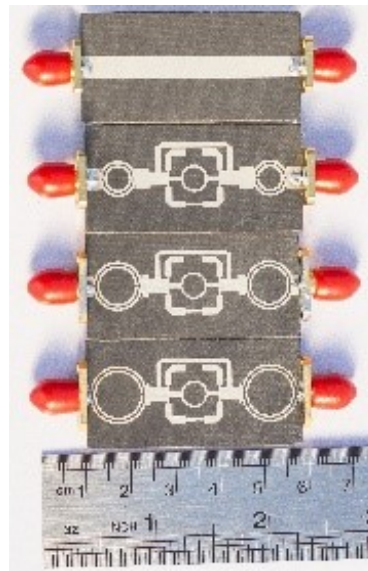
$\Delta\phi$	60°	75°	90°
L_1	10	10	10
L_2	4	4	4
L_3	4	4	4
L_4	0.5	1.5	3
L_{u1}	15	15	15
L_{u2}	5.5	5.5	5.5
W_1	1.5	1.5	1.5
W_2	0.5	0.5	0.5
W_3	3	3	3
W_4	4.68	4.68	4.68
W_u	1	1	1
W_s	0.5	0.5	0.5
r_s	3	3	3
l_m	48	48	48
W_m	24	24	24
a	1.2	1.2	1.2
b	1.2	1.2	1.2
c	2.4	2.4	2.4
L_{ext}	14.4	14.4	14.4

Table 3: Dimensions of metamaterial phase alignment network main lines for phase shifts of 60° , 75° and 90° . (Units in mm)

$\Delta\phi$	60°	75°	90°
r_{ext}	6.5	5.5	4
d	0.5	0.5	0.5
W_r	0.4	0.4	0.4



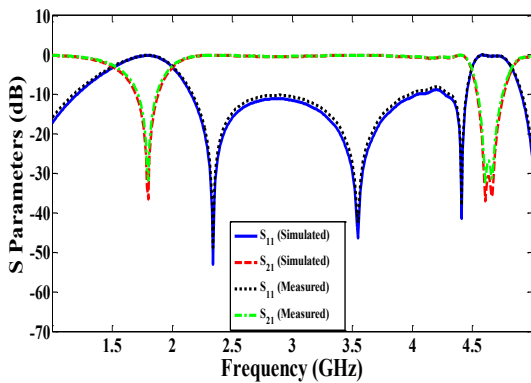
Bottom side



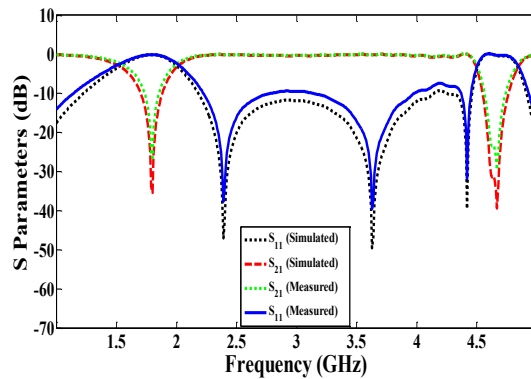
Top side

Fig. 8. Photograph of the fabricated phase shifters for arbitrary phase shift values.

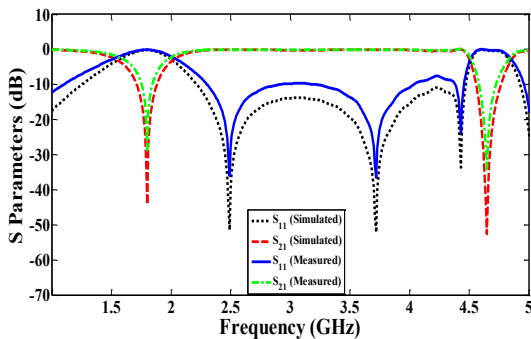
The simulated and measured frequency S-parameter response of the phase shifters in Fig. 9 show that the return-loss and insertion-loss are better than 10 dB and less than 0.5 dB, respectively, over 2.2 to 4.4 GHz. There is also good agreement between the simulated and measured results.



(a)



(b)



(c)

Fig. 9. S-parameter response of the three phase shifters, (a) 60° delay line, (b) 75° delay line, and (c) 90° delay line.

The phase differences of the proposed DPSs are shown in Fig. 10. The delay lines maintain constant phase shifts of 60°, 75° and 90° across a bandwidth of 2.2 to 4.4 GHz. The measurements show that the phase shifters have less than 4° differential phase stability.

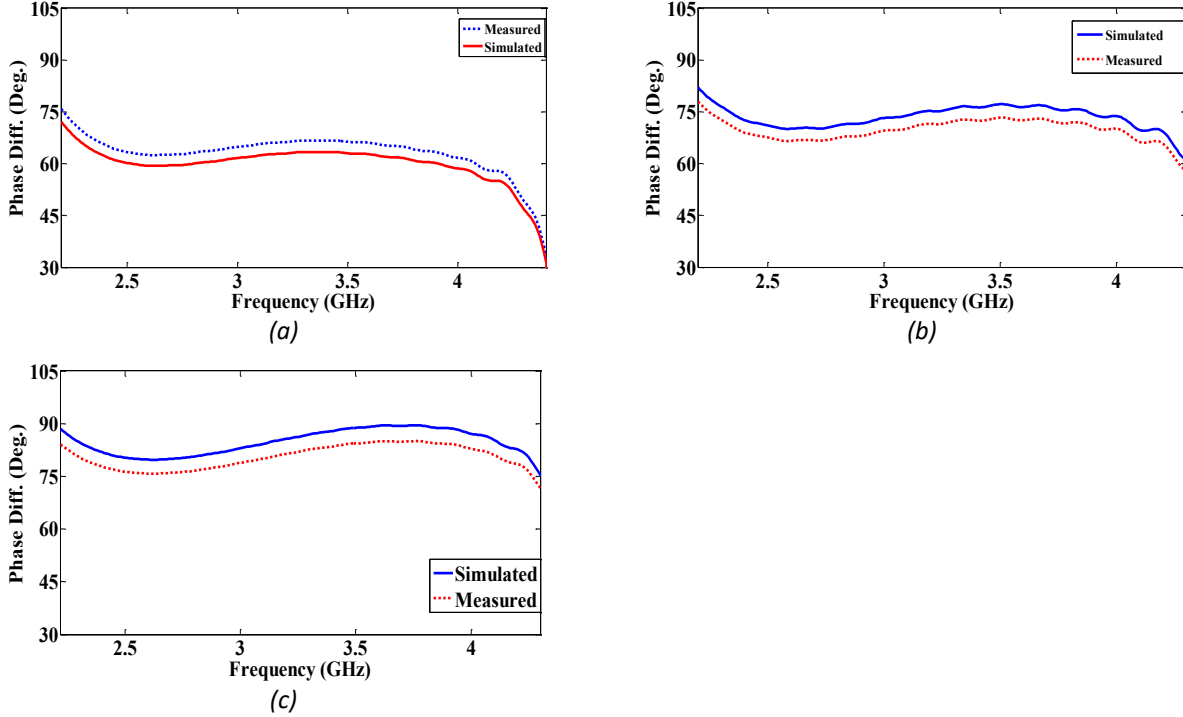


Fig. 10. Simulated and measured phase response of the DPSs, (a) 60°, (b) 75°, and (c) 90°.

The proposed DPS design is compared with the other DPSs in Table 4, which reveals that the proposed DPS achieves better results compared with the previously reported DPSs except that its bandwidth of 88% is lower than the structures in [5], [9] & [10]. This is because these structures have a longer main line that supports a larger phase shift. The proposed DPS is compact as all lines are of equal length that is achieved with metamaterial phase alignment networks.

TABLE 4: Comparison of the proposed phase shifter with previous works

Ref.	Multi-way poly-phase	Phase shift values (°)	Universal Ref. line	Equal line lengths	Equal length ref. line	BW (%)	Metamaterial phase Align. Net.	IL (dB)	Max. PD (°)	Size (λ_0)
[4]	No	90	No	No	No	82	No	<0.6	± 6.4	-
[5]	No	90	No	No	No	101.5	No	<1.2	± 5	-
[7]	No	90	No	No	No	80	No	<2.3	± 4	-
[8]	No	45-90	Yes	No	No	80	No	<1.1	± 4.5	0.42×0.25
[9]	No	45-180	No	No	No	100	No	<0.6	± 8	0.5×0.3
[10]	No	90	No	No	No	107.7	No	<0.5	± 5	-
[11]	Yes	45, 90, 180	Yes	No	No	40	No	<0.9	± 5	-

[12]	Yes	45, 90, 135	Yes	No	No	45	No	<0.9	±5	-
[13]	Yes	45-135	Yes	No	No	55.6	No	<0.7	±5.8	-
[14]	Yes	30-90	Yes	Yes	No	65	No	<1.24	±5	-
[15]	Yes	34	Yes	Yes	No		No	<1.5	±1.5	4×0.5
This work	Yes	60-90	Yes	Yes	Yes	88	Yes	<1	±4	0.56×0.28

5. Conclusion

The feasibility of a novel class of equal length multi-way poly-phase wideband differential phase shifter is demonstrated. The phase shifter is based on metamaterial technology. Compared to phase shifters based on SRR reported to date the proposed structure provides larger phase shifts by simply adjusting a single parameter of the metamaterial structure and is also significantly smaller. Compared with conventional phase shifters, the proposed phase shifter has advantages of a compact design, wide frequency band of operation and offers a large range of phase shift angles. The phase angle can be accurately controlled by changing the radius of SRRs constituting the phase shifter. The phase shifter's performance was verified through measurement.

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